Research Program on the
Management of Science and Technology

ACCURACY OF TECHNICAL ESTIMATES IN INDUSTRIAL RESEARCH PLANNING*

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Accuracy of Technical Estimates In Industrial Research Planning

by

Dennis L. Meadows* and Donald G. Marquis+

Abstract

To understand the estimate errors which must be accommodated by formal project selection models, this study investigates the relationships among initial estimates and actual outcomes in industrial product-development programs. The following preliminary conclusions are based on data from five commercial laboratories:

1. The estimate errors employed in current selection procedures can lead management to expend more than 50 percent of the firm's development resources on technically or commercially unsuccessful projects.

2. Unsuccessful projects tend to incur greater cost overruns and to cost more on the average than do projects resulting in commercially successful products.

3. Current estimates are not sufficiently accurate to justify the use of formal selection formulas. The most accurate estimates of project cost explain only 25% of the variance among actual costs. Initial estimates of probability of technical or commercial success do not usefully distinguish among projects which have different degrees of success.

4. The average magnitude of cost overruns and the rate of commercial success depend in part on the source of the project idea.

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Introduction

One fact must disturb anyone interested in improving the administration of industrial research and development programs. Although no aspect of laboratory administration has received more attention in the management science literature than has project selection procedure, there appears to be almost no implementation of the formal selection models which have been proposed. Baker and Pound's review of the project selection literature included over 80 different formal models, all proposed for use in evaluating development project proposals.[1] Their study of implementation found that only six laboratories out of thirty-five have experimented with even one of the models. None of the thirty-five administrators were currently using such a model in their laboratories. A survey of R&D policy in U.S. chemical companies in Chemical and Engineering News also found a low reliance on formal models in the selection of new product development projects.[2] The prevalent attitude was characterized by one of the administrators interviewed in the study.

> We've played around with several formulas, but we decided that they give no more insight than does mature judgment by management.[3]

As a nation we invest about $25 billion annually in R&D activity. Many firms spend from 5% to 10% of their gross sales income on R&D programs. Most of this money is invested in product development and improvement programs, the phase of R&D for which formal selection models have been specifically proposed. Management science models have made an important contribution to other areas of management. If we aspire to increase the effectiveness of our investment in new technology, it is important to understand why current efforts by management scientists in developing project selection models have borne so little fruit. The reasons underlying that failure must have implications for the design and use of such models.

Estimate Error

In their study of implementation, Baker and Pound conclude that formal models have not been implemented because they have not been specifically designed to fit the intrinsic structure of the project selection decision. One important aspect of that problem is the models' universal failure to recognize and take account of any errors in the estimates which constitute their inputs.

The uncertainty in estimates is the difficulty which most laboratory directors first note in any formal model. Again the C&EN study provides a characteristic remark:

> Formulas mean nothing. They are just an accumulation of approximations and assumptions, which may not have any relation to reality.[4]

Of course there are other important obstacles to the use of the current formal models.

- Each development project must typically serve many incommensurate and often conflicting goals. It is neither valid not useful to evaluate the project's total contribution along only one dimension, yet the output of most models is a single index of value.

- The laboratory is a complex social system with many subtle influences on individual performance. The procedure which assigns resources among competing projects is a major determinant of employee satisfaction. Thus personnel considerations must enter into the selection and use of any project evaluation model. The management science models currently available do not consider such factors.

- The costs and returns of any given development project depend in complex ways upon the nature of other projects undertaken by the laboratory. The great majority of all formal models evaluate each project individually, ignoring the interdependencies.

Of the obstacles listed above, estimate error is the most important factor in the failure of formal project selection models. It is primarily through estimate errors that the other three structural problems affect the selection decision:

- Even models designed to evaluate a project proposal along several different dimensions must rely upon estimates of the relevant attributes, and errors in those estimates will limit the utility of the models.

- When the selection rule does not fit its organizational milieu, experiments suggest that employees can respond by deliberately biasing the estimates used in the decision rule.[5]

- Interdependencies among the costs and payoffs of different projects, which are ignored by the selection rule, will manifest themselves through outcomes which differ from those anticipated, ie. through estimate errors.

In short, estimates are the vital link between any selection procedure and the organization which employs it. All organizational and technical factors which must enter into the design of a formal project evaluation procedure and which determine its effectivenss can be expressed in terms of their impact on the difference between estimated and actual project outcomes. Laboratory managers are of course only interested in the actual outcomes of their projects. However, the rules they employ in allocating resources among alternative projects must be based primarily on estimates of those outcomes. Social and technical factors can both lead, in theory, to deviations between the initial estimates and the actual outcomes.

The experience of laboratory administrators apparently suggests that the errors introduced by these factors are large enough to prevent current formal models from being useful in the selection decision. It is thus naive to propose any model and anticipate its implementation in the laboratory without first understanding the relationships between estimated and actual project outcomes.

Errors and Current Models

Current selection formulas almost completely ignore the difficulties introduced by estimate errors. Where the problem of uncertainty is even acknowledged, its solution is implicitly left to the administrator.

> The procedures developed here can be applied where projects can be classified into groups which have different probabilities of success and where the necessary estimates can be obtained with an acceptable degree of accuracy.[6]

No operational criteria are given for determining exactly when or how such estimates can be generated. Nor is there a discussion, typically, of what constitutes "an acceptable degree of accuracy". One author even concluded after a survey of formal project selection models and a discussion of the estimates upon which they

were based, that "measuring the accuracy of these estimates would be difficult if not impossible."[7]

Measurement of estimate errors is indeed difficult, as Marshall and Meckling discovered while assessing the uncertainty inherent in the development of Air Force weapon systems.[8] Problems are introduced by changes in the price level, in the magnitude of the production run, and in the objectives of the project. The widespread use of ambiguous estimates which do not explicitly state assumptions about interdependent variables also complicates measurement of errors. However, Marshall's study of cost and time overruns, and that of Peck and Scherer,[9] did prove it possible to derive useful conclusions from such research.

The most important conclusion of both studies corroborates the subjective judgment of laboratory administrators. Estimate errors can be, and often are, very large. Marshall and Meckling report the average ratio of final cost to the earliest estimate (adjusted for changes in output and in price level) as follows:

9 fighter planes	1.7
3 bombers	2.7
4 cargoes and tankers	1.2
6 missiles	4.1

Peck and Scherer reported an average ratio of 3.2 for 12 planes and missile developments. Schedule slippage on 10 programs was conservatively determined by Marshall and Meckling to range from 2 years to 5 years, with an average ratio of final completion time to earliest estimate of 1.5. The corresponding ratio for the 12 programs examined by Peck and Scherer was 1.36.

If industrial development programs are also characterized by the uncertainties found in these military studies, none of the formal models currently proposed can provide much assistance to management in selecting among projects. However, government programs characteristically differ from industrial projects in magnitude, in organizational environment, and in the amount of technological advance required. Thus it is difficult to assess the relevance of the findings to

commercial programs.

Mansfield has undertaken the only detailed study of estimated and actual outcomes in a large sample of industrial product development projects.[10] However, he obtained no data on the commercial outcomes of the projects, and his measurement of probability estimating performance is not based on the meaning which laboratory administrators typically assign to those estimates.

We have discovered no other published study assessing the nature of errors in the estimates employed to select among alternative commercial development projects. After their extensive review of the literature Baker and Pound reported, "no references were found which attempted to give data and discuss the actual role of uncertainty in R&D project selection."[11]

It obviously is impossible to eliminate uncertainity from development programs, but as we come to understand the influence of various social and technical factors on estimate error, we can design selection procedures which will best take account of uncertainty in specific laboratories. The present study is designed to explore systematically the relation between estimated and actual outcomes in commercial development projects. Large scale studies of many more projects in both industrial and defense laboratories are currently in process.

Data Sources

Data from five firms will be utilized here to discuss several of the preliminary findings.* Three of the laboratories are in chemical companies engaged primarily in the development, production, and sale of industrial intermediates. Two of the chemical firms, A and B, have between $100 million and $300 million annual sales. The third is one of the largest firms in the nation. The fourth laboratory, called here the Electronics Laboratory, is maintained by an instrumentation company

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* "A detailed data appendix, from which company and project titles have been eliminated, is available on request from the Program Office, M.I.T. E52-539, Cambridge, Mass. 02139."

We acknowledge the assistance of Kenneth Seltzer in compiling and analyzing a portion of the data.

to engage in work of interest to NASA and the Department of Defense. The fifth set of project data is taken from Mansfield's article describing his study of a central research unit in a prominent equipment manufacturer.

Data from each of the five laboratories were obtained from three sources. The initial estimates of project cost, probability of technical success, and probability of commercial success were obtained from project evaluation forms completed at the time the project was first approved for funding. Accounting records supplied the actual costs, and the leader of each project indicated whether the project had eventually been technically and/or commercially successful.

Completed projects are divided into four categories according to their outcomes.

Miscellaneous failure: The project was closed out because of manpower shortages, changes in the market objectives of the firm, or other non-technical reasons. The project did not result in a product.

Technical failure: The project was closed out when unforeseen technical difficulties prevented the development program from producing the desired product.

Commercial failure: The project did produce the product initially desired, but it did not produce any sales income for the firm.

Commercial Success: The project was technically successful, and the product did produce sales income for the firm.

The classifications of technical and commercial success are dichotomous. With the exception of Chemical Laboratory B, no attempt was made to rank products on the basis of their technical or commercial performance. The above definitions do not apply to the projects in Chemical Laboratory C where the estimated and actual costs for only one year's development on each project were available.

Conclusions

1) Current laboratory selection procedures typically expend more than 50% of the firms development resources on projects which do not produce commercially successful products. (Table 1)

Table 1

LABORATORY INVESTMENT IN UNSUCCESSFUL PROJECTS

% TOTAL COST

<table>
<tr><th>Project Outcome</th><th>Chem Lab A</th><th>Chem Lab B</th><th>Electronics Lab</th><th>Equip. Lab</th></tr>
<tr><td>Miscellaneous Failure</td><td rowspan="2">45%(1)</td><td rowspan="2">18%</td><td>10%</td><td>27%</td></tr>
<tr><td>Technical Failure</td><td>25%</td><td>20%</td></tr>
<tr><td>Commercial Failure</td><td>37%</td><td>51%</td><td>18%</td><td rowspan="2">51%(2)</td></tr>
<tr><td>Commercial Success</td><td>18%</td><td>31%</td><td>47%</td></tr>
</table>

(1) Project leaders responded to the question, "Did the project achieve its technical objectives?" Thus no distinction was made between technical and miscellaneous failures.

(2) Mansfield did not obtain information on the commercial outcome of the projects in his study. Thus it is impossible to distinguish between those projects which were commercially successful and those which were only technically successful. Rounding errors prevent percent total actual cost from equaling 100%.

The total cost of unsuccessful projects is a qualitative measure of uncertainty. The remaining conclusions relate technical and organizational factors to estimate uncertainty.

2) There is a pronounced tendency for technically and commercially unsuccessful projects as a group to incur greater cost overruns than commercially successful projects. (Table 2)

When projects are grouped according to their outcomes, the ratio of total actual to total estimated costs for the unsuccessful projects of each laboratory is found to be greater than for the corresponding group of successful projects.

3) Technically and commercially unsuccessful projects cost more on the average than commercially successful projects. (Table 2)

4) There is a low correlation between the actual and estimated values of cost, probability of technical success, and probability of commercial success figures employed in selecting among projects. (Figures 1-4)

Table 2

AVERAGE PROJECT COST AND COST OVERRUN BY PROJECT OUTCOME

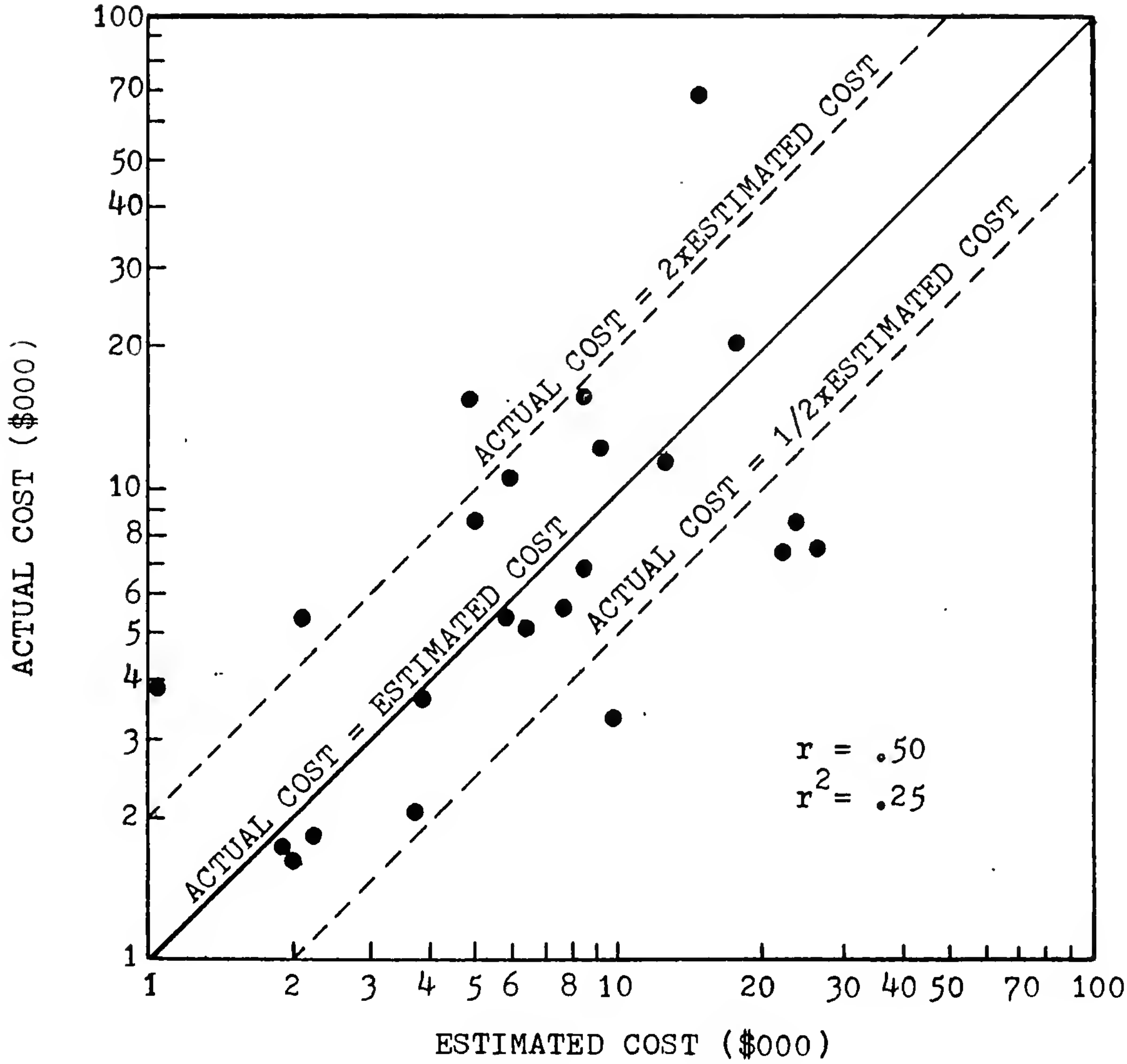
Laboratory Project Outcome	# Projects	Total Actual Cost / Total Estimated Cost	Average Cost Per Project
Chem Lab A			
Miscellaneous & Technical Failure	7	2.55	$20,780
Commercial Failure	11	1.28	$14,200
Commercial Success	12	0.94	$ 6,430
Chem Lab B			
Miscellaneous & Technical Failure	4	3.84	$ 2,690
Commercial Failure	12	4.25	$ 2,520
Commercial Success	17	1.27	$ 1,070
Electronics Laboratory			
Miscellaneous Failure	7		1.4 man-yrs
Technical Failure	5		4.8 man-yrs
Commercial Failure	8		2.2 man-yrs
Commercial Success	22		2.1 man-yrs
Equipment Laboratory			
Miscellaneous Failure	12	.96	(1) 1.5%
Technical Failure	7	1.25	2.9%
Commercial Failure & Commercial Success	20	0.96	2.5%

(1) Costs are given as a percentage of the total laboratory expenditure on the 45 projects.

Cost Estimates

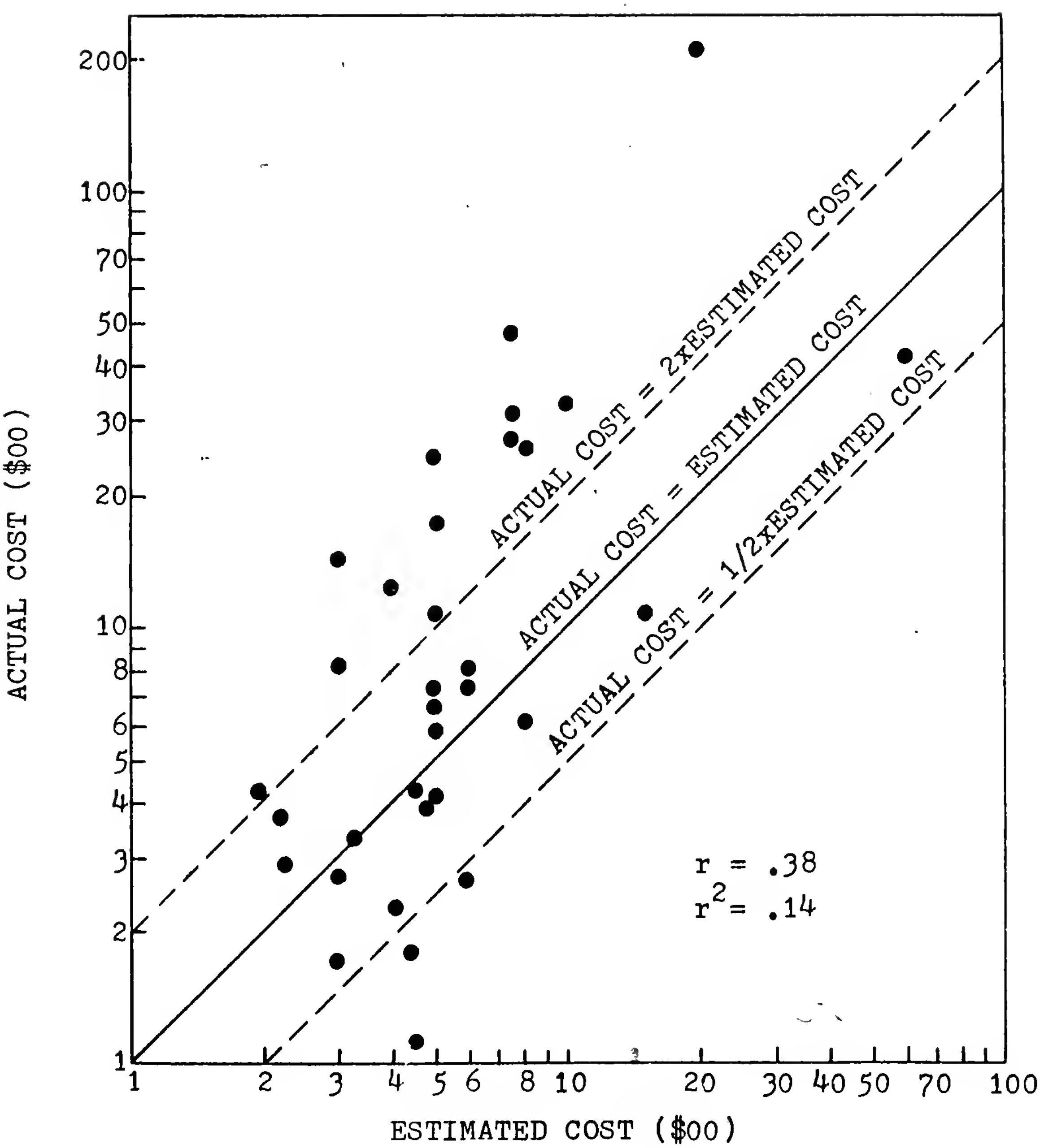
In Chemistry Laboratories A and B, the cost of successfully meeting the technical requirements is predicted for each project before deciding whether it should be funded. The actual costs of projects which were technically successful can thus be compared with the initial estimates to measure the error in those estimates. Figures #1 and #2 compare estimated with actual costs for each of the two organizations.

The actual costs are generally found to differ substantially from those initially predicted. Where there are deviations of this type, it has been suggested



ESTIMATED vs. ACTUAL COSTS FOR 23 TECHNICALLY SUCCESSFUL PROJECTS - CHEMICAL LABORATORY A

Figure 1



ESTIMATED vs. ACTUAL COSTS FOR 33 TECHNICALLY SUCCESSFUL PROJECTS - CHEMICAL LABORATORY B

Figure 2

that a linear formula in the form:

$$\text{Actual Cost} = A + (B)(\text{Estimated Cost})$$

be employed to modify the initial estimates, correcting for the errors inherent in them.[12] It is easy to determine statistically the "best" linear formula for any given set of historical data, but many factors limit the predictive ability of such an equation by causing some deviation of the actual costs from the modified estimates. The correlation coefficient, r, measures this deviation. The quantity r^2 indicates what percent of the variance in actual costs is explained by the modified estimates. If r (consequently r^2) is low, the estimates will be of little use in predicting actual costs. The correlation coefficient for each set of projects is given on the corresponding figure. The most accurate estimates, those in Chemical Laboratory A explain only 25% of the variance in the actual project costs even when they are modified with the best linear correction formula for that particular set of data:

$$\text{Actual Cost} = \$596 + 1.45\ (\text{Estimated Cost})$$

In Chemistry Laboratory C project costs are predicted for only one year at a time. The uncertainty in annual cost estimates should be substantially less than that in the estimates of total project costs. The estimates are more accurate than those found in the other chemistry laboratories. However, the estimates still account for no more than 57% to 74% of the variance in actual costs.

Probability Estimates

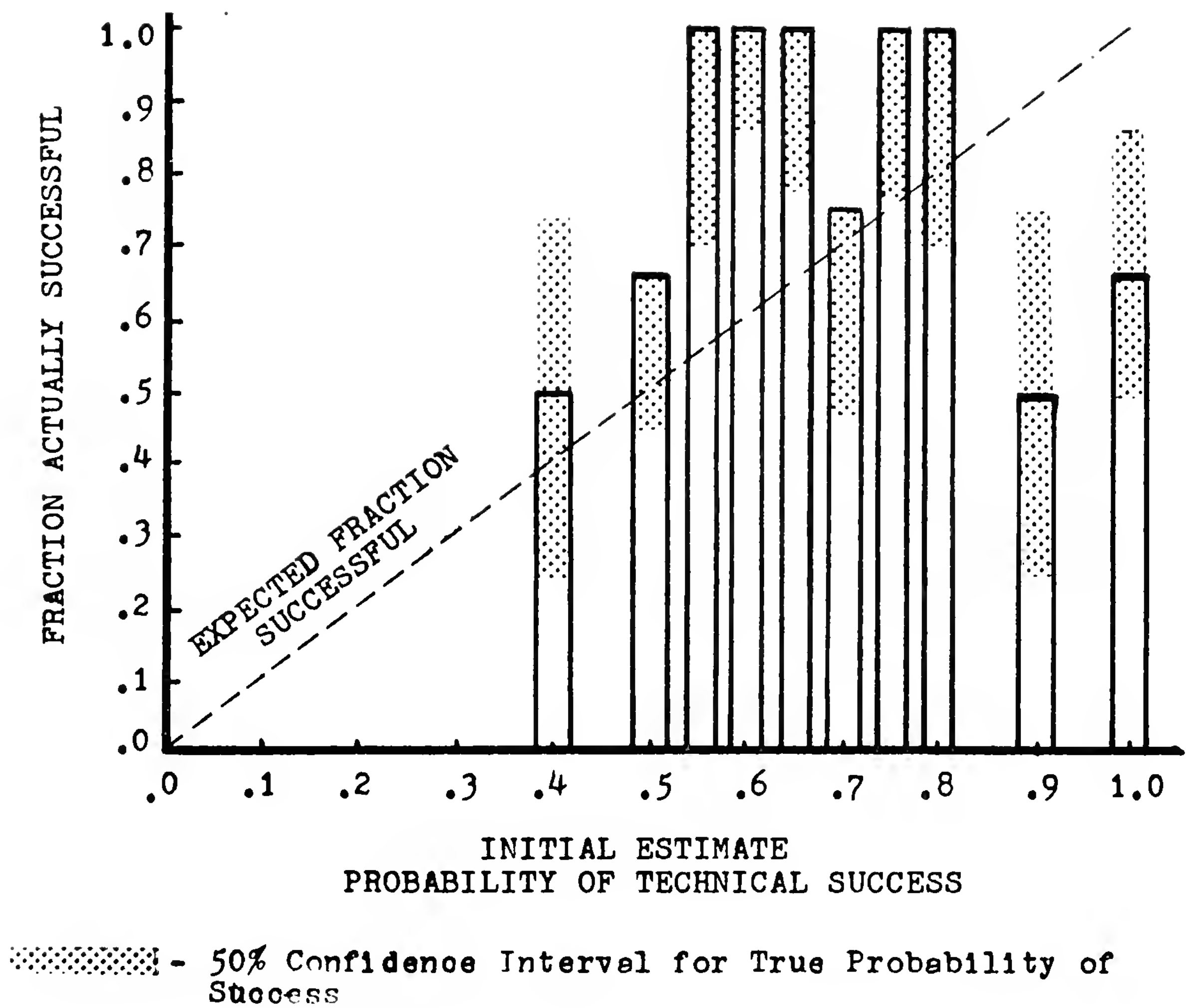
The staffs of Chemical Laboratory A and the Equipment Laboratory estimate the probability of technical success and the probability of commercial success of each development project before deciding whether it should be funded. The estimated values are employed by management as if they characterized a binomial process. For example, of all the projects which receive the initial estimate PTS = 0.80, 80% are expected to be technically successful.

Probability estimate errors are more difficult to measure than cost estimate errors. A numerical overrun ratio can be employed to indicate the error in an

estimated cost figure. There is no equivalent measure of probability estimate error. When a coin lands with one side up on eight of ten losses, it does not necessarily disprove the initial estimate that the probability of that side landing up is 0.50. Similarly, a deviation between the fraction of projects which actually succeed and the probability of technical success initially assigned a set of projects does not necessarily prove the initial estimate to have been in error. A deviation of the fraction actually successful from that expected on the basis of the initial estimate is particularly likely to occur when there are only a few projects in the group. Thus only statistical measures of probability estimate error are possible.

To measure the accuracy of the probability of technical success estimates in Chemistry Laboratory A, all projects were divided into groups according to the probability of technical success value each project was initially assigned. The estimated probability of technical success values are indicated on the horizontal axis of Figure #3. The fraction of each group which actually succeeded was determined and the fractions are indicated by vertical white bars. Finally, that fraction which was technically successful was used to calculate limiting values of the true probability of success. From the fraction actually successful in each set of projects, an interval was found which has a 50% probability of including the true, but unknown, probability of technical success. These 50% confidence intervals are shown in Figure #3 as shaded bands. Although the procedure is complicated, it is not difficult to interpret the results. If half the shaded bands cross the line indicating the expected fraction successful, the initial estimates have not been proved inaccurate.

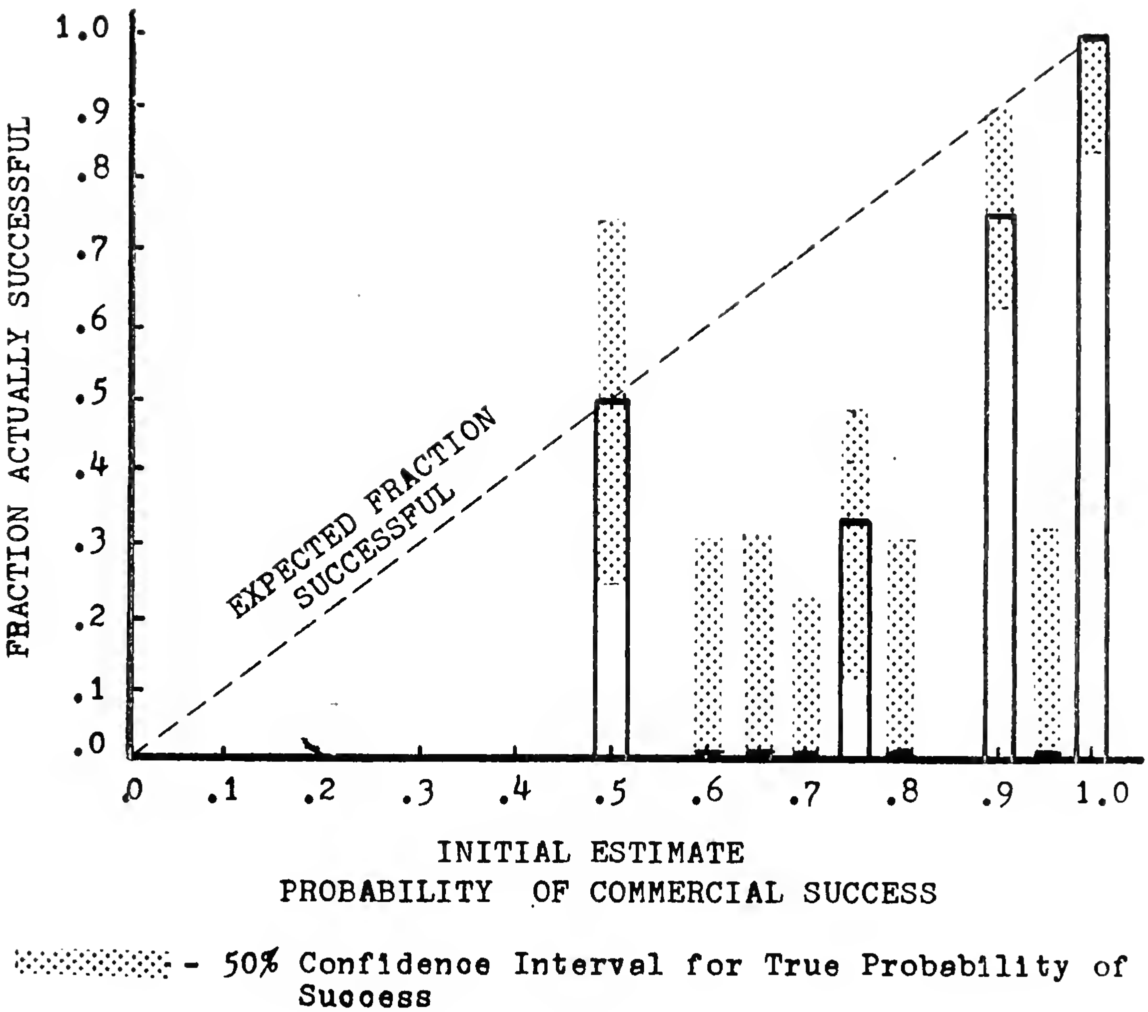
The measurement of probability of commercial success differs from the above in only one respect. Each estimate of probability of commercial success is based on the assumption that the project will be technically successful. Thus only the 20 technically successful projects are included in the analysis shown in Figure #4.



ACCURACY: ESTIMATED PROBABILITY OF TECHNICAL SUCCESS

30 PROJECTS, CHEMICAL LABORATORY A

Figure 3



ACCURACY: ESTIMATED PROBABILITY OF COMMERCIAL SUCCESS

20 PROJECTS, CHEMICAL LABORATORY A

Figure 4

The results tend to confirm the laboratory management's belief that market estimates are less reliable than technical estimates.[13] Figures #3 and #4 indicate that the initial probability estimates in Chemistry Laboratory A are not accurate enough to be employed in project evaluation formulas.

Mansfield assigned a different meaning to the Equipment Laboratory probability of technical success estimates. Thus his analysis of estimate error differs from that described above. Nevertheless, he too concluded that, "although there is a direct relationship between the estimated probability of success and the outcome of a project, it is too weak to permit very accurate predictions."[14]

5) The average magnitude of cost overruns and the rate of commercial success may differ depending upon the sources of the project idea. (Tables 3 & 4)

<u>Cost Overruns</u>

In Chemistry Laboratory B the source of the project idea was recorded. It is thus possible to determine the average cost overrun of projects initiated by the laboratory, by the marketing staff, or by a customer. The results are summarized in Table #3.

Table 3

AVERAGE COST OVERRUN BY PROJECT SOURCE

CHEMICAL LABORATORY B

Project Idea Source	Average $\frac{\text{Actual Cost}}{\text{Estimated Cost}}$
Laboratory	2.20
Marketing Department	2.02
Customer	1.27

The different overruns in Table #3 probably correspond to the magnitude of technological advance attempted in each group of projects. Customers tend to request only product modifications, while laboratory personnel are inclined to suggest more difficult technical problems. The marketing staff would tend to

fall between the two extremes. This interpretation is supported by a study of military development programs. Marshall and Meckling classified 26 programs into three degrees of required technological advance and found the overrun factor to be 1.4 for small, 1.7 for medium, and 3.4 for large technological advances.[15]

Rate of Success

Projects in Chemistry Laboratory B which were initiated at the suggestion of customers have a much greater probability of commercial success than projects originating in either the marketing department or the laboratory. Table #4 gives the percent of each project group which resulted in no sales, small, medium, or large sales. The expenditure invested in projects from each source is also included in the table. Taken together, Tables #3 and #4 suggest that the magnitude of uncertainty associated with a development project may be related to the project's source.

Table 4

COMMERCIAL OUTCOME BY PROJECT SOURCE

CHEMICAL LABORATORY B

Project Source	Percent of Projects Laboratory	Marketing	Customer
Incremental Sales			
None	66%	58%	33%
Small	17%	14%	33%
Medium	17%	14%	13%
Large	0%	14%	20%
	100%	100%	100%
Percent of Total Budget Expended	40%	40%	20%

Discussion

The magnitude of the errors presented above is characteristic of all the laboratories studied, but the assessment of its ultimate generality must await more data from other laboratories. However, each of the companies above is considered a technical leader by the others in its field. Each company is profitable and growing. One cannot dismiss the seemingly poor estimating performance as the result of inept technical staff or poor management. Many types of important estimates have not yet been studied, but probability of technical success and project cost are the two parameters which laboratory managers feel they can estimate most accurately.[16] Thus we do not expect that other types of estimates will be found more reliable.

Unless the laboratories we have studied are atypical, estimate error must be the first concern of laboratory managers interested in incorporating formal models into their project evaluation decision. As models differ in structure, they will differ in their sensitivity to the errors in different estimates. Figures #1 and #2 suggest that the same estimates, project cost in this example, in similar laboratories can still have widely differing error characteristics. It is therefore impossible for a manager to assess the relative value of different selection models in his own laboratory until he better understands the nature of the errors inherent in the estimates available to him. This inevitably will involve each organization in a study of its own estimating procedures and capabilities.

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14. Mansfield, op. cit. p. 462

15. Marshall, op. cit. p. 472.

16. Seiler, op. cit. p. 177.